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TeV Scale Quantum Gravity and Mirror Supernovae as Sources of Gamma Ray Bursts

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Abstract

Mirror matter models have been suggested recently as an explanation of neutrino puzzles and microlensing anomalies. We show that mirror supernovae can be a copious source of energetic gamma rays if one assumes that the quantum gravity scale is in the TeV range. We show that under certain assumptions plausible in the mirror models, the gamma energies could be degraded to the 10 MeV range (and perhaps even further) so as to provide an explanation of observed gamma ray bursts. This mechanism for the origin of the gamma ray bursts has the advantage that it neatly avoids the "baryon load problem".

I. INTRODUCTION

The origin of the gamma ray bursts (GRBs) observed for over three decades still remains unclear [1]. The GRBs are short, intense photon bursts with photon energies in the keV and MeV range although bursts with energy spectra extending above a GeV have been observed. The isotropy and $\frac{dN}{dV}$(intensity) distributions and the high redshift galaxies associated with some GRBs indicate that the sources of GRBs are located at cosmological distances. The specific nature of the sources remains however unclear.

If unbeamed, the sources must emit total γ-ray energies of 10^{51} to 10^{53} ergs [1][1] This is very much reminiscent of typical supernova energies. However, most supernovae (e.g. type

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[1]Beaming reduces this by $\frac{\Delta\Omega}{4\pi}$ and increases the required burst rate by $\frac{4\pi}{\Delta\Omega}$ over the few per day seen in the universe.

II supernovae) cannot be these sources, since γ-rays with typical radiation lengths of 100 gm/cm^2 cannot penetrate the large amount ($\sim 10\ M_{\odot}$) of overlying ejecta.

Many of the models for unbeamed (beamed) GRBs use massive compact sources to produce neutrinos which annihilate to form fireballs of e^+e^-'s and γ's [2,3]. The fireballs expand and cool adiabatically, until the temperature (or the transverse energy) is low enough so that the e^+e^- annihilate into the γ's. To avoid the 'baryon load" problem and the absorption of γ's, fairly "bare collapses" are required [4]. Accretion induced collapses and binary neutron star mergers [1] were considered but it is not clear whether these are sufficiently "baryon clean". One "baryon clean" source candidate based novel particle physics is a neutron star to strange quark star transition.

Other recent suggestions [5,6] invoked the existence of sterile neutrinos [7]. If the emitted neutrinos undergo maximal oscillation to the sterile neutrinos [5], the latter can penetrate the baryon barrier and subsequently normal neutrinos will appear via the $\nu_s - \nu$ oscillation. In this scenario, the last "back" conversion occur at relatively large distances [2] and the $\nu\bar{\nu} \to e^+e^-$ which goes like R^{-8} [2] is inefficient[3]. Similar difficulties are encountered by models utilizing exact "mirror" symmetric theories [9] where the sterile (mirror) neutrinos emitted in a mirror star collapse oscillate into ordinary neutrinos.

In this note, we propose another GRB scenario in the context of the asymmetric mirror models [10]. It utilizes the conversion of $\nu' + \bar{\nu}', \gamma' + \gamma' \to e^+e^-, \gamma\gamma$ etc inside the mirror star, where primed symbols denote mirror particles. Since the familiar electrons and photons do not interact with mirror matter, the expanding fireball is not impeded and we have an ideal bare collapse. The resulting photons expected to have initial energies of $\approx$ GeV, can be processed in this expansion down to the MeV part of the GRB spectra observed. Furthermore, if the source is embedded in the disk of a galaxy, further degrading can take place due to the "minibaryon load" of the disk resulting in keV gamma rays as well as possibly structure in the gamma ray spectrum.

The key requirement is that the conversion process be fast enough so that a finite fraction of the collapse energy is indeed converted into ordinary matter. As we will see this naturally obtains [11] if we can have a low scale (of order of a TeV) for quantum gravity [12][4]

In section 2 we give a brief review of the assumptions of mirror matter models within which we work. In section 3 we outline our scenario, computing the initial γ energies, and

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[2]Both $\nu \to \nu_s$ and $\nu_s \to \nu$ are quenched by dense matter if $\Delta m^2 \leq 10^4$ eV^2 [8].

[3]Disklike (and beamed) geometry may partially alleviate this problem.

[4] In the p-Brane construction, ordinary and mirror matter could reside on two sets of branes [13] with a relatively large (compared to $\Lambda^{-1} \approx (TeV)^{-1}$) separation r_0. The gauge group is of the form $G \to G_{matter} \times G_{mirror}$ where each $G = SU(3) \times SU(2)_L \times U(1)_Y$. The detailed model implementing this scenario will have to be such that it can lead to enhanced amplitude for the four Fermi operators that lead to familiar particle production via the collision of mirror particles whereas suppressed coefficient for the ones that lead to neutrino mixing. The latter in general involve exchange of fermions and the desired suppression is therefore not implausible. We thank Markus Luty for discussions on this point.

a brief discussion of possible fireball mechanism for degradation of the photon energies. We also discuss the effect of a baryon cloud ("mini-baryon load") which can lead to further degradation of gamma energies. We work within the framework of TeV scale gravity using the results of Silagadze [11] for the production of familiar matter from mirror matter. We conclude in section 4 with a brief discussion.

II. ASYMMETRIC MIRROR MODEL AND LARGE SCALE STRUCTURE IN THE MIRROR SECTOR

Let us begin with a brief overview of the asymmetric mirror matter model and the the parameters describing fundamental forces in the mirror sector. In asymmetric mirror matter models [10], one considers a duplicate version of the standard model with an exact mirror symmetry [15] which is broken [10] in the process of gauge symmetry breaking. Denoting all particles and parameters of the mirror sector by a prime over the corresponding familiar sector symbol (e.g. mirror quarks are u', d', s', etc and mirror Higgs field as H', mirror QCD scale as Λ') we assume that $< H' > / < H >= \Lambda'/\Lambda \equiv \zeta$ [16]. This is admittedly a strong assumption for which there is no particle physics proof, but it does provide a certain degree of economy. Of course, if one envisioned the weak interaction symmetry to be broken by a new strong interaction such as technicolor in both sectors, then it is possible to argue that such a relation emerges under certain assumptions.

There also exists a cosmological motivation for assuming $< H' > / < H >= \Lambda'/\Lambda \simeq 15$. One can show that in this case the mirror baryons can play the role of cold dark matter of the universe [16,17]. The argument goes as follows: one way to reconcile the mirror universe picture with the constraints of big bang nucleosynthesis (BBN) is to assume asymmetric inflation with the reheating temperature in the mirror sector being slightly lower than that in the normal one [18]. Taking the allowed extra number of neutrinos at the BBN to be 1 implies $(T'_R/T_R)^3 \leq 0.25$. One can then calculate the contribution of the mirror baryons to Ω to be

$$\Omega_{B'} \simeq (T'_R/T_R)^3 \zeta \Omega_B \tag{1}$$

Since one expects, under the above assumption, the masses of the proton and neutron to scale as the Λ in both sectors, if we assume that $\Omega_B \simeq 0.07$, then this implies $\Omega_{B'} \simeq 0.26$ leading to a total matter content $\Omega_m \simeq 0.33$. Thus familiar and mirror baryons together could explain the total matter content of the universe without need for any other kind of new particles.

An important implication of this class of mirror models is that the interaction strengths of weak as well as electromagnetic processes (such as Compton scattering cross sections etc) are much smaller than that in the familiar sector. This has implications for the formation of structure in the mirror sector.

Structure formation in a similar asymmetric mirror model was studied in Ref. [19] where it was shown that despite the weakness in the mirror particle processes, there are cooling mechanisms that allow mirror condensates to form as the universe evolves. The basic idea is that the mirror matter provides gravitational wells into which the familiar matter gets attracted to provides galaxies and their clusters. However due to weakness of the physical

processes, the mirror matter is not as strongly dissipative as normal matter. So for instance in our galaxy, the familiar matter is in the form of a disk due to dissipative processes whereas mirror stars which form the halo are not in disk form. In contrast, in the symmetric mirror model [9], the mirror matter would also be in a disk form and therefore could not help in explaining observed spherical galactic halos. Furthermore, since mirror matter condensed first in view of the lower temperature, it is reasonable to expect that mirror star formation largely took place fairly early (say $z \geq 1$) and the subsequent rate is much lower. In what follows to understand the observed GRBs we would require a mirror star formation rate of about one per million year per galaxy (to be contrasted with about 10/year/galaxy for familiar stars).

In the asymmetric mirror model, it has been shown that there are simple scaling laws (first reference in [16]) for the parameters of the mirror stars: (i) the mass of the mirror stars scale as ζ^{-2}; (ii) the radius of the mirror stars also scales like ζ^{-2} whereas (iii) the core temperature scales slightly faster than ζ. Here ζ denotes the ratio of the mass scales in the mirror and familiar sectors and is expected to be of order 15-20 from considerations of neutrino physics [10]. Due to the higher temperature of the mirror stars, they will "burn" much faster and will reach the final stage of the stellar evolution sooner. Because of the ζ^{-4} decrease of weak cross sections and the increase in particle masses we do not expect mirror star collapse to result in explosion. Rather there should be neutrino emission and black hole formation. Thus we would expect that there will be an abundant supply of mirror "supernovae." We will show in the next section that these could be the sources of the GRBs.

III. LOW QUANTUM GRAVITY SCALE AND PRODUCTION OF FAMILIAR PHOTONS IN MIRROR SUPERNOVAE

In a mirror supernova, one would expect most of the gravitational binding energy to be released via the emission of mirror neutrinos as in the familiar case. However, in the asymmetric mirror matter model, we expect the temperature of the collapsing star to be higher. We have $NT = GM^2/R$ where N is the number of mirror baryons in the star (about $M_\odot/(\zeta m_p)$. At $\zeta = 10$ the maximum mirror star mass is about $M_\odot$ so that T is about a GeV where we have taken the radius of the collapsed mirror star to be about a kilometer. Let us now estimate the production cross section for the familiar photons in the collision of the mirror photons in the core.

The most favorable case occurs if we assume that the quantum gravity scale is in the TeV range [11]. In this case, assuming two extra dimensions [12] and following reference [14], we estimate the cross section $\sigma_{\gamma'\gamma'\to\gamma\gamma}$ to be,

$$\sigma_{\gamma'\gamma'\to\gamma\gamma} \simeq \frac{1}{10}\frac{s^3}{\Lambda^8} \tag{2}$$

where s is the square of the total center of mass energy. For $s = 1$ GeV^2 and $\Lambda \simeq 1$ TeV, we get, $\sigma_{\gamma'\gamma'\to\gamma\gamma} \simeq 10^{-52}$ cm^2. We estimate the rate of energy loss per unit volume to into familiar, not mirror, photons to be roughly

$$\frac{dQ}{dtdV} \simeq c n_{\gamma'}^2 2E_{\gamma'}\sigma_{\gamma'\gamma'\to\gamma\gamma} \tag{3}$$

Multiplying by the volume of the one kilometer black hole gives about 10^{52} erg/s. This energy is of the right order of magnitude for the total energy release in the case of unbeamed or mildly beamed GRBs. However the initial energy of individual photons obtained via $\nu' \to \gamma$ conversion is essentially that of the mirror neutrinos i.e. $E_\gamma(t=0) \approx E_{\nu'} \approx 3T_{mirror}$. The spectrum of the latter- just like that of ordinary neutrinos obtained in the core cooling of ordinary type II supernovae- is expected to be roughly thermal with $T_{mirror} \approx$ GeV, which is roughly 100 times higher than for familiar collapse.

While in some GRBs, photons of energies in the range of GeVs to TeVs have been observed, the bulk of the spectrum is in the MeV/keV region. Reprocessing the initial photons leading to energy degradation is therefore important. Two distinct mechanisms contribute to reprocessing: (i) Fireball evolution and (ii) Overlying putative familiar material. Let us discuss both these mechanisms.

Mechanism (i):

At t=0, we have, because of universality of gravitational interactions an equal number of familiar e^+e^- produced with the photons. The resulting dense $e^+e^-\gamma$ "fireball" constitutes a highly opaque plasma. There is an extensive literature dealing with the evolution of such fireballs [2,4]. In the case where this evolution is free from the effects of overlaying matter (i.e. the effects of (ii) are negligible), the discussion becomes almost model independent and many features can be deduced from overall energetics and thermodynamic considerations. Thus at t=0 when a fraction ϵ of the mirror neutrinos convert to γ's (and/or e^+e^-'s), the latter have a blackbody spectrum with temperature $T_{\nu'}$. However the overall normalization, i.e. the energy density

$$U_\gamma = \epsilon U_{\nu'} = \epsilon a T_{\nu'}^4 \tag{4}$$

falls short by a factor ϵ of the universal black body energy density at such a temperature. Fast processes of the form $\gamma\gamma \to e^+e^- \to 3\gamma$ (allowed in the thermal environment) will then immediately reequilibrate the system at

$$T_\gamma \sim \epsilon^{\frac{1}{4}} T_{\nu'} \approx \left(\frac{1}{3} - \frac{1}{30}\right) T_{\nu'} \tag{5}$$

(corresponding to GRB energies between $10^{48} - 10^{52}$ ergs and mirror supernova energies of $10^{52} - 10^{53}$ ergs). Subsequent evolution can further increase N_γ and correspondingly decrease $\overline{E}_\gamma$ down towards the MeV range. Independent of this, mere expansion reduces the transverse photon energy according to $E_\gamma^{tr} \approx (R/r)T_\gamma(t=0)$, where R is the size of the source and r is the current γ location. (The last expression which parallels that for adiabatic cooling simply reflects the geometrical convergence of trajectories of colliding γ's which become more and more parallel with distance r.) Since E_{tr} controls the center of mass energy of the $\gamma\nu$ collisions, the $\gamma\gamma \to e^+e^-$ processes become kinematically forbidden and the density of e^+e^- pairs falls exponentially i.e. $n_{e^+e^-} \approx e^{-\frac{m_e}{T_{tr}(r)}}$ eventually leaving freely propagating γ's.

Mechanism (ii):

A "mini-baryon load" of familiar material encountered by the outgoing γ's could further reduce the photon energy. Also the presence such matter in conjunction with mild beaming could induce the very short time structure often observed.

In order to have an effective degrading of the emitted photon energies, we will need an appropriate density of familiar matter which can be estimated as follows. Let us assume a density profile of the form:

$$\rho(R) = \frac{\rho_0 R_0^2}{R^2 + R_0^2} \tag{6}$$

Then we demand the constraint that $\int \rho(R)dR \simeq 100$ gm/ cm^2 where 100 gm/cm^2 represents the radiation length of photons in matter. This implies $\rho_0 R_0 \simeq 100$ gm/cm^2. The kinematical requirement of having comoving baryonic plus fireball system requires

$$\gamma_B \equiv \frac{f W_{GRB}}{M_{Baryo}} \approx \gamma_{Fireball} \approx \frac{E_{e^+e^-}}{2m_e} \tag{7}$$

where f is the fraction of energy imparted to baryons and γ_B is the Lorentz factor. Using $M_{baryo} \approx \frac{4\pi}{3}(\rho_0 R_0)R_0^2$, we find

$$R_0 = 10^{12}\ cm\ \left[\frac{(W/(10^{50}\ ergs))}{(E/100\ MeV)(\rho_0 R_0/100\ gm\ cm^{-3})}\right]^{1/2} \tag{8}$$

so that for the nominal values of the total GRB energy, the fireball processed energy of individual e^+, e^-, γ and the column density, we find $R_0 = 10^{12}$ cm so that $\rho_0 = 10^{-10}$ gr/cm^3 and $M_{baryo} \approx 10^{25}\ gr \simeq 10^{-8} M_{\odot}$. It is interesting to note that in the present scenario, GRB's originating from mirror supernovae in the galactic halos, which most likely would not face the "minibaryon load", may have only the first stage i.e. energy degradation by fireball mechanism and hence will have a harder spectra and smoother time profile. (Clearly discerning such a component in the GRB population will be quite interesting.) On the other hand the GRBs originating from supernovae in the disk of galaxies will have degradation due to both mechanisms and therefore more structure in the spectra as well as a softer spectra.

Beyond the immediate neighbourhood of the mirror star there would be further energy degradation from interaction with interstellar matter ranging from molecular clouds to interstellar comets. There is not however sufficient material in one kilopersec to overcome the small value of the Thompson cross section i.e. $n_e \sigma_T \ell \sim 10^{-2}$ as against a required value of one.

IV. DISCUSSION

Section 3 shows, we believe, that mirror matter supernovae, within the asymmetric mirror matter model, can provide a plausible explanation for gamma ray bursts. The scenario requires some coupling between the mirror and familiar sectors. In Section 3, we have used the couplings provided by TeV range quantum gravity following the estimate of reference ([11]), but other coupling mechanisms (such as a small $\gamma - \gamma'$ mixing) might be possible as well. Given TeV scale gravity, it is noteworthy that the same value of ζ required by other

"manifestations" of mirror matter gives both an appropriate upper limit to the energy of the familiar gammas produced and an appropriate cross section section for their production. A major advantage of this GRB explanation is that it solves the baryon load problem in a natural way. In this model, we would expect production of GeV neutrinos at nearly the same rate as e^+e^- and $\gamma\gamma$ etc. For GRBs located in our galaxy, they should be observable in detectors such as Super-Kamiokande.

If this model is correct, given the short lifetime of the mirror stars [16], the GRB frequency of 10^{-6}/year/galaxy must be a result of low mirror star formation rate, which as mentioned above is not an unreasonable assumption.

Finally, it is tempting to speculate that, if the primary GRB mechanism is to produce a fireball in the many MeV temperature range, there should exist a GRB population with temperatures in that range. In view of the fact that most of the data on GRBs comes from BATSE detector which triggers mostly on γ's below 300 keV, it appears that such a population is not necessarily excluded by current data.

This possibility that mirror matter can explain GRBs adds to a growing list of arguments that asymmetric mirror matter should be taken seriously. These include: (1) the requirement in many string theories that mirror matter exist; (2) the fact that the same range for ζ that was required in Section 3 for GRBs gives a mirror neutrino at the proper mass difference from ν_e to be the sterile neutrino responsible for simultaneously solving all the neutrino puzzles; (3) the fact that the same range of ζ gives an appropriate amount of dark matter to give an overall Ω_M in the range 0.2 to 0.3; and (4) the fact that the same range of ζ gives an explanation of the MACHO microlensing events as being caused by mirror black holes of about $M_{odot}/2$ mass.

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